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Study of Modal Characteristics of a geared rotor system

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Abstract

Modal analysis is used to determine the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes. These parameters are important in the design of a system for dynamic loading conditions. Conventionally, modal analysis is performed with specific commercial tools. On the other hand, modern FEA softwares have good potential to perform modal analysis studies. This work attempts modal analysis using solid elements in ANSYS Workbench of a geared rotor system supported on ball bearings at the ends. This has been carried out to study the natural frequencies in different modes, to predict the direction of whirl of various modes as well as to study Campbell diagram. . In the end, effect of variation in bearing stiffness has been found out on natural frequencies in various modes of the geared rotor system.

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*Keywords:*Modal analysis;gear rotor system; mode shapes; Campbell diagram;

1. Introduction

Gearbox is a complex structure and is the combination of rotary parts and stationary parts. Due to spin induced forces, vibrations generate in the geared rotor system and gear meshing considerably affects these vibrations. There are many studies in transverse and torsional vibration analysis of gear systems ([1] – [4]). However studies combining axial, transverse and torsional vibration and those also using solid models are not found much in literature. It is important to include all these considerations in the analysis to get a complete idea about the dynamic characteristics of gear rotor systems.

Modal analysis is a technique used to determine, improve and optimize dynamic characteristics of engineering structures [5]. It can be used for determining the inherent dynamic characteristics of a system in forms of natural

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frequencies, damping factors and mode shapes. To better understand any structural vibration problem, the resonances of a structure need to be identified and quantified. A common way of doing this is to define the structure's modal parameters [6]. Many studies about modal analysis of gear rotor systems have been reported in literature, e.g. Kahraman et al. [7] developed a FE model of a geared rotor system on flexible bearing considering rotary inertia of shaft, axial loading on shaft, flexibility and damping of bearing, stiffness and damping of gear mesh and concluded that bearing compliances can greatly affect the dynamics of geared system. Modal dynamic behaviour of gear pair system can be affected by manufacturing errors in gear tooth which is studied by DriotandPerret-Liaudet [8].

Above studies show that dynamic characteristics of gear rotor system can be identified with the help of much relied Finite element (FE) analysis. FE analysis can be performed by following numerical simulation approach or by developing a model in any commercially available FE analysis software. The aim of this work is to build a gear rotor model in FEA software and to assess its dynamic capabilities by performing modal analysis. This work helps out in understating the results of natural frequencies, modal damping and mode shapes, reported for the gear rotor system.

2. Numerical Example

The geared rotor-shaft system as shown in Fig. 1 has been considered for the purpose of simulation. The gear pair is mounted on a 30 mm diameter uniform steel shaft of length 254 mm. Gears are located at the centre of shaft as shown in the Fig. 1. The location, geometry and other properties of the gear system are given in Table 1 and it is assumed to be made from steel with a Young's modulus of 210 GPa, Poisson's ratio of 0.3 and a density of 7850 kgm^{-3}.

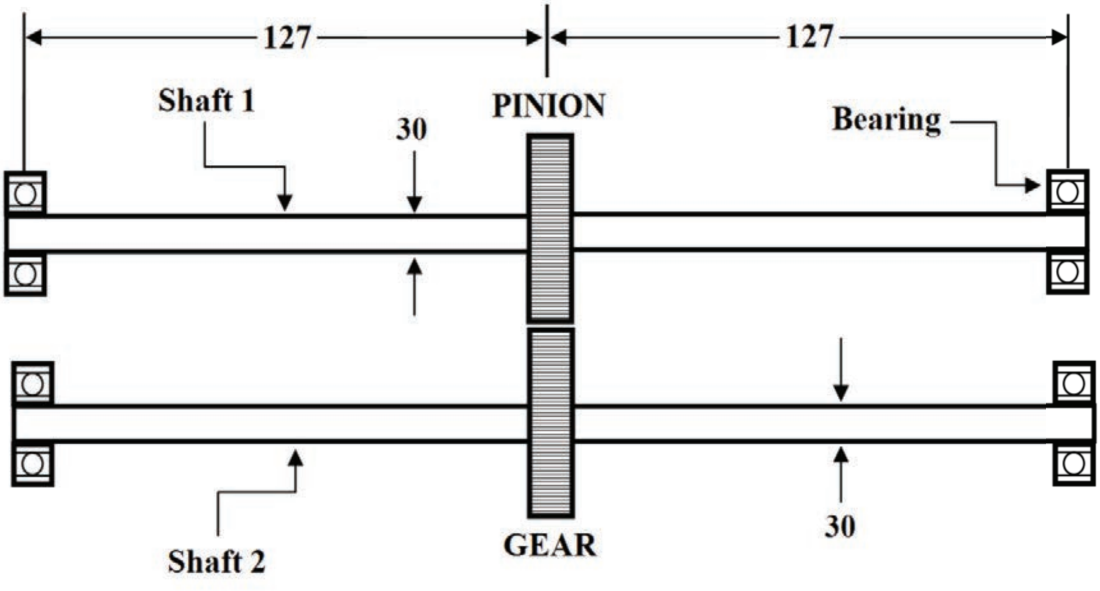


Fig. 1. A schematic diagram of geared rotor system (All dimensions are in mm.)

Table 1 Parameters of the spur gear system

	Gear	Pinion
Number of teeth	25	24
Module	5	5
Pressure angle	20^0	20^0
Pitch circle diameter (m.)	0.125	0.12
Facewidth (m.)	0.01	0.01
Mass (kg.)	1.09	0.975
Mesh stiffness (N/m)	1×10^8	
Bearing stiffness (N/m)	1×10^9	
Bearing damping (N-s/m)	200	

3. Detailed methodology of modeling gear rotor shaft

This section describes the methodology for the present work. Firstly, the 3D model of the gear rotor system has been created using ADAMS software using the dimensions mentioned in Table 1. The ADAMS machinery gear module supports multiple combinations of gear type and modelling methodology options. This work uses the option of "Detailed" analysis which is useful for calculation of contact forces between the gear pair using involute function and user defined contact properties analytically. The parameters like gear contact stiffness and other parameters are included during this process. The 3D rotor model as created in ADAMS software is shown in Figure 2. The rotor model thus created has been converted into IGES (Initial Graphics Exchange Specification) format and exported to analysis software. The shaft and the bearings are modelled in the ANSYS workbench itself and in this way the final model consisting of gear, pinion, rotor-shaft, and the bearings is created. In this work the software ANSYS workbench has been used for the meshing as well as modal analysis and post processing.

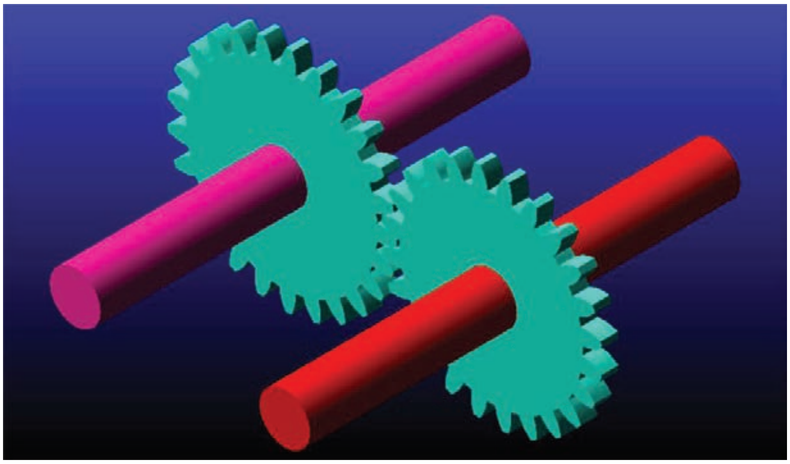


Fig. 2 3D model of the gear rotor system created in ADAMS

4. Result and discussion

The solid gear shaft model has been modelled in ANSYS workbench software. In ANSYS workbench, the material density of rotor-shaft and discs, Young's modulus of rotor shaft are set. Bearing connections are provided at both the ends of the rotor-shaft. The values used for bearing stiffness and damping are mentioned in Table 1. After giving all the necessary values and connections in ANSYS workbench software, the final model is obtained as shown in Fig. 3. After solving this model the natural frequencies and mode shapes are analysed for further studies. Table 2 lists the natural frequencies of system after performing modal analysis. Mode shapes and natural frequencies obtained after performing modal analysis can be validated by Ref. [7] which shows that the first natural frequency of gear system reduces due to coupling of gears and is occurred due to gear mesh stiffness. Also the bending and torsion modes shown in Fig. 4 (a)-(e) are same as obtained in Ref. [7].

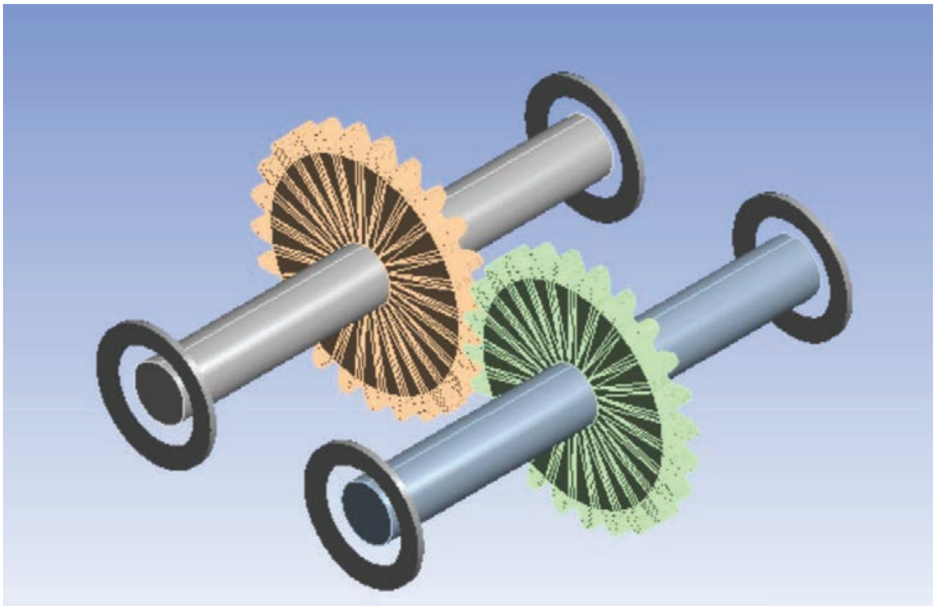


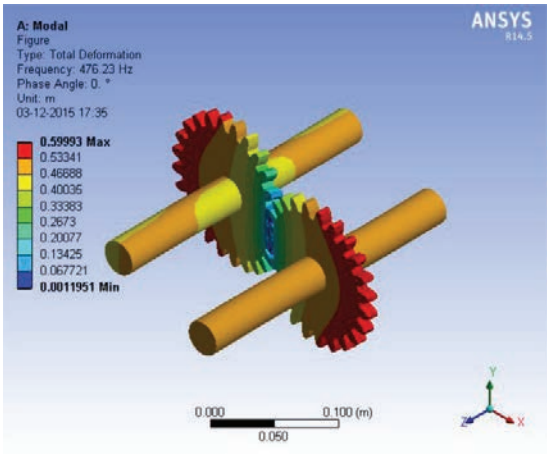
Fig. 3 Gear rotor shaft model in FE software

Table 2Natural Frequencies of system

Mode	Frequency [Hz]
1	476.23
2	541.09
3	620.32
4	620.84
5	1268.6
6	2074.8
7	2228.7
8	2260.5
9	2663.1
10	3693.6

4.1 Mode shapes of gear rotor system

Natural frequencies generally account for the structural mass and stiffness distributions. Mode shape patterns corresponding to the natural frequencies can be informative for structural design consideration or other monitoring purposes. Fig. 4 ‘a’ –‘d’, show the first four bending modes of the geared rotor system. It has been found that the fifth natural frequency corresponds to the first torsional mode as shown in Fig. 4 ‘e’.



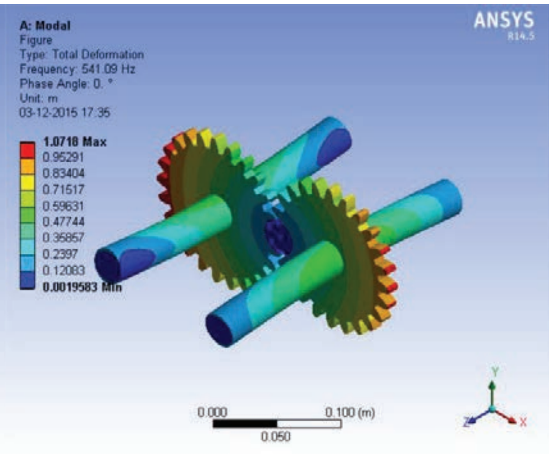
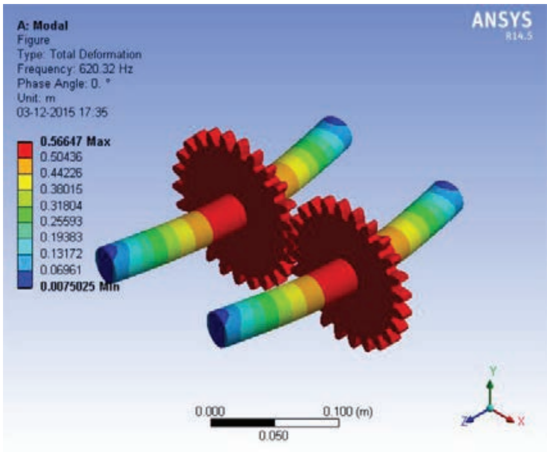


Fig. 4(a) First bending mode due to transverse vibration; Fig. 4(b) Second bending mode due to transverse vibration



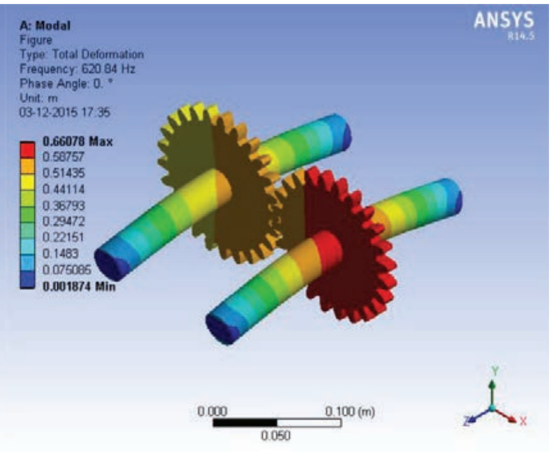


Fig. 4(c) Third bending mode due to transverse vibration; Fig. 4(d) Fourth bending mode due to transverse vibration

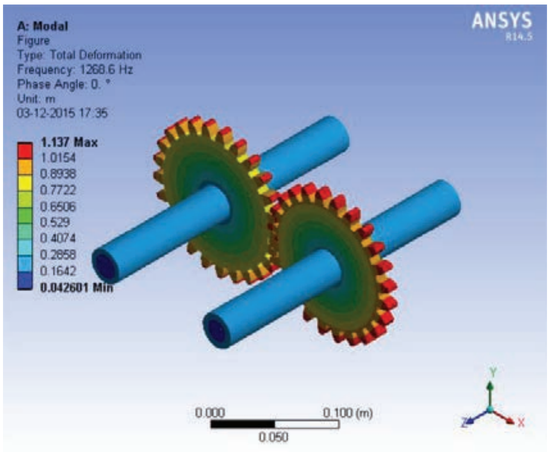


Figure 4 (e) First torsion mode due to torsional vibration

4.2 Campbell diagram of gear rotor system

Campbell diagram is a plot which shows variation of natural frequencies of the rotor system with spin speed. This diagram is also used to find out critical speeds of the rotor system as points of intersection of the excitation order lines with the lines of natural frequencies. This helps in finding out safe operating speed regions for the rotor system. Ten spin speeds are considered in plotting the Campbell diagram. These speeds are 0 to 9000 rpm in the interval of 1000 rpm.

Fig. 5shows the Campbell diagram (also called whirl speed map) of the gear rotor system. A synchronous whirl line (ratio =1) has also been plotted to find out the critical speed due to unbalance excitation. The intersection of this line with the line representing first forward mode gives the first critical speed of the system. For the soft and intermediate type of bearings, the rotor does not bend for the initial two modes and these modes are known as “rigid rotor modes”. First two modes shown in Fig. 5have almost negligible natural frequency and are due to effect of rigid body motion of the system. It can also be seen that because of gyroscopic effect, each natural frequency of whirl (mode) is split into two frequencies (modes) when rotor speed is not zero [9]. As the rotor speed increases, this gyroscopic moment stiffens the system stiffness of the forward whirls and weakens the system stiffness of the backward whirl. Also the gyroscopic moment shifts up the forward whirl frequencies and shifts down the backward whirl frequencies.

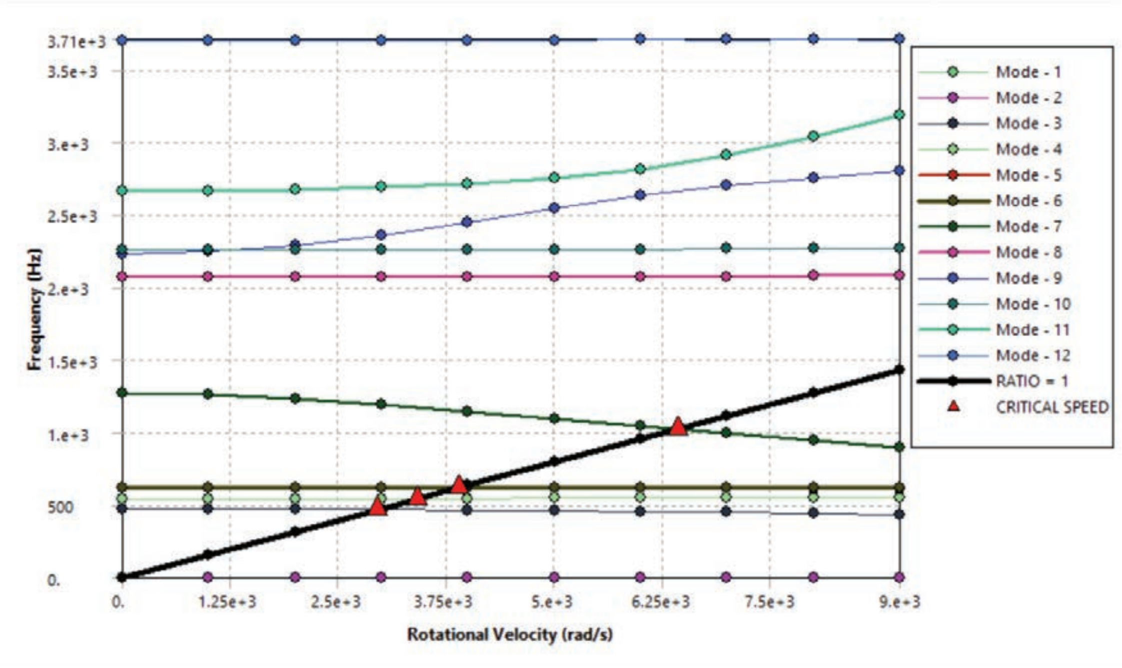


Figure 5 Campbell diagram of gear rotor system

4.3 Effect of bearing compliance on gear rotor system

Bearing compliance directly affects the modal behaviour of any rotating structures. In this paper gear rotor system are assumed to be supported by isotropic ball bearings at the end. To study the effect of bearing stiffness on this system, bearing stiffness are varied from 1×10^7 (N/m) to 1×10^{10} (N/m) as in this range only bearing stiffness varies. It has been found that natural frequencies are greatly affected by this variation as can be seen in the Fig. 6. Effect on first torsional mode is less as compared to first four bending modes.

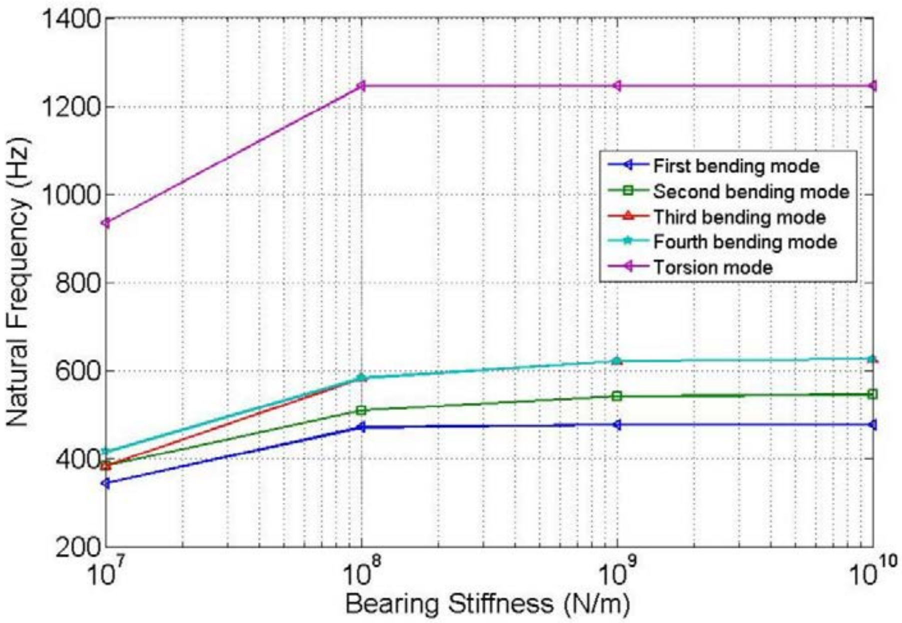


Figure 6 Variation of natural frequencies due to bearing compliance

5. Conclusion

A finite-element model is developed to study the dynamic behaviour of geared rotor system using FEA software. The results of natural frequencies and their corresponding mode shapes are reported. It has been found that first four modes are bending modes due to transverse vibrations whereas fifth mode is torsion mode which is due to torsional vibration. Effect of whirl speed on natural frequencies of the system is also studied in Campbell diagram which shows that forward whirl frequencies increase with the increase in rotational speed and the backward whirl frequencies decrease with increase in rotational speed. Finally, it has been shown that the bearing compliances can considerably affect the dynamics of geared systems. The plot shows that by varying the stiffness values of bearings used to support the gear rotor shaft significantly affects the value of natural frequencies. This type of study may be helpful in understanding modal behaviour of geared rotor systems. In future, modal analysis using experimental approach will be tried for similar type of gear rotor system.

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